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Sequential sampling for pest control programs

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Sequential sampling for pest control programs

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ABSTRACT

In comparison with traditional sampling techniques, sequential sampling reduces the number of samples required to evaluate a population level by 40-80%. This reduction lowers monitoring costs and facilitates the implementation of an integrated pest management program. This paper reviews four prerequisites imposed by this technique and compares the advantages and limitations of the methods used by Wald in the United States and by Iwao in Japan. It also describes the calculation methods used and provides a practical example of the use of Poisson and negative binomial distributions.

RÉSUMÉ

La technique de l'échantillonnage séquentiel permet de réduire de 40 à 80% le nombre d'échantillons nécessaires à l'évaluation d'un niveau de population par rapport aux techniques traditionnelles d'échantillonnage, favorisant ainsi la mise en place d'un programme de lutte intégrée. Les quatre éléments prérequis à l'utilisation de cette technique ainsi que les avantages et les limites de l'approche américaine de Wald et de l'approche japonaise d'Iwao sont présentés. Les méthodes de calcul et un exemple pratique illustrant l'utilisation de cette technique d'échantillonnage sont donnés pour les distributions de Poisson et de la binomiale négative.

CONTENTS

INTRODUCTION

Problems related to the use of massive amounts of chemicals in pest control have served to create an increasing awareness of the importance of diversifying existing pest control programs. The theory of integrated management can provide a solution, by offering a series of steps that can be taken before having to resort to chemical treatments (Luckman and Metcalf 1975).

The implementation of an integrated pest management (IPM) program implies a reduction in the number of chemical treatments applied and in the amount of chemicals used per treatment. Reducing the amount of chemicals applied decreases the risk that the pest population will develop a resistance to the product and generally leads to a decrease in the cost of production. However, to ensure the success of this type of program, pest population levels must be monitored throughout the growing season (Boivin and Vincent 1981).

Monitoring the levels of the pest populations before or after treatment requires a regular program of field sampling, which involves a significant commitment in terms of human and economic resources. Nevertheless, sampling remains essential to the IPM program, providing information on the crop under study. Therefore, the grower or some other qualified person should learn how to sample in such a way as to obtain this information as efficiently as possible.

Ruesink and Kogan (1975) describe two sampling techniques for estimating population levels. The spatial distribution of the organism can be used to determine the optimal number of samples that must be obtained to estimate the average density of the pest population within certain predetermined limits of error (Karandinos 1976). This number of samples represents a compromise: it is too high when the population level is high, and too low at low population densities. When the population level is near the economic threshold, there is a maximum probability of reaching the wrong conclusions (Fohner 1981).

As the purpose of sampling is to make recommendations for intervention, the aim is simply to determine whether the pest population is above or below a certain economic threshold. Sequential analysis makes it possible to arrive at this objective while reducing the number of samples required.

Sequential sampling was developed during the Second World War (Wald 1943, 1945, 1947). Its great success in programs used to control the quality of military equipment led to its classification as a 'military secret' in the United States until 1945, when it was finally made public. Shortly after that, it was applied to forest entomology (Morris 1954, Waters 1955) and later to agricultural entomology (Sylvester and Cox 1961, Harcourt 1966a, b). Since then, sequential sampling has been used to determine the population levels of insects in many different crops (Pieters 1978).

Sequential sampling evolves by successive stages and the decision to intervene may be made after each sampling. Once a critical level is reached, namely the economic threshold, sampling stops and a recommendation is made.

In cases of heavy infestation, several samples may show that the pest population still remains above the economic threshold. On the other hand, if, after several samples, no pests are captured, one may be reasonably sure that the population level is low. By virtue of this principle, sequential sampling makes it possible to make quick decisions within a preestablished margin of error, reducing the number of samples required by 47-63% (Wald 1947), or even up to 79% in some cases (Pieters and Sterling 1974), in comparison with the more traditional sampling techniques described by Cochran (1977).

This method can be used in all plant protection disciplines that require estimations of population levels, particularly in entomology, plant pathology, and nematology.

Sequential sampling can also be used to evaluate the effectiveness of insecticide treatments in the field and to determine whether parasite and predator populations are high enough to avoid an intervention. Kuno (1969, 1972, 1977) has used this technique to estimate population means within known error limits. Johnson (1977) has estimated sex ratios in insect groups captured with sticky traps by examining them sequentially. Dichotomized data (e.g. sex ratios, infected versus healthy plants) can also be treated with this technique. Thus, sequential sampling has become a very useful tool for determining the optimal utilization of the resources required to evaluate population parameters.

The purpose of this paper is to show the advantages and disadvantages of the techniques used by Wald (1947) in the United States and by Iwao (1975) in Japan.

PREREQUISITES

Four elements are necessary to establish a sequential sampling program:

- a practical and reliable sampling procedure
- the economic threshold of the organism in a particular crop
- the parameters of a mathematical model describing the spatial distribution of the sampled organism
- realistic and acceptable error levels for estimating pest populations in crops.

The following is a review of these prerequisites.

SAMPLING TECHNIQUES

Sampling techniques can be either direct (when the pest is captured) or indirect (when using effects left by the organism, such as waste products or indications of damage). The same technique must be used to obtain the economic threshold and the spatial distribution of the organism. When more than one developmental stage is studied, the relative effectiveness of the technique used must be determined so that the estimates can be adjusted by means of appropriate weight factors.

ECONOMIC THRESHOLD

The economic threshold is the population level above which an intervention becomes necessary (Stern 1973).

For better precision, this threshold should be established for each cultivar, because the susceptibility of plants varies from one cultivar to another. Thus, the economic threshold is a function of crop value and pest control cost.

The use of Wald's method (1947) requires the establishment of two critical population levels: λ_1 (level below which no treatment is required) and λ_2 (level above which treatment is recommended)[1]. The choice of the interval between λ_1 and λ_2 is based on the biology and behavior of the pest, crop value, and the potential damage that may be caused by the pest (Waters 1974). The probability of arriving at a correct classification is lower when the population level is between λ_1 and λ_2 than when the population level is below λ_1 or over λ_2 (Fohner 1981). The smaller the interval between λ_1 and λ_2, the larger the number of samples required.

When the economic threshold is unknown, a sequential sampling plan can be implemented on the basis of a preliminary threshold, called the action level by Lincoln (1978). This provisional level may be used with certain reservations regarding the precision of the sampling or the recommendations made.

SPATIAL DISTRIBUTION

The spatial distribution of the pest population determines the number of samples required to arrive at a predefined level of precision. The calculation of the limits of this zone of acceptability varies according to whether the distribution of the organism is uniform (Fig. 1A), random (Fig. 1B), or contagious (Fig. 1C).

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[1] Mathematical symbols are defined in the glossary at the end of this bulletin.

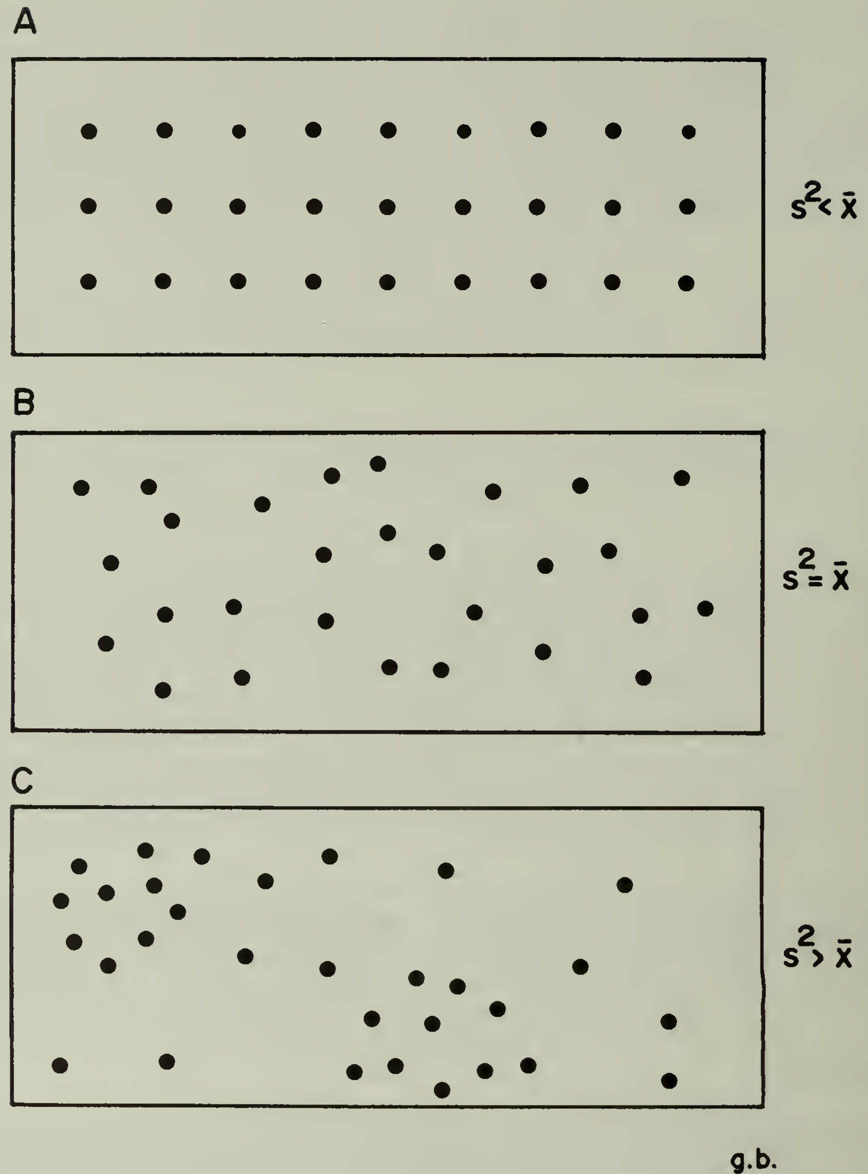

Fig. 1. (A) Uniform, (B) random, and (C) contagious distributions.

Two methods can be used to characterize the spatial distribution of an organism. The first consists of obtaining samples and then comparing the frequency distribution of the captured organisms with theoretical distributions such as Poisson, Poisson binomial, or negative binomial. The fit between the observed and theoretical frequency distributions can be quantified by tests such as G, χ^2, or Kolmogorov-Smirnov (Sokal and Rohlf 1981).

The second method characterizes the spatial distribution of an organism by using the mean crowding index (Lloyd 1967) in relation with Iwao's regression technique (1968). This method makes it possible to describe spatial distribution on the basis of two parameters (Iwao 1977) and implies a calculation method that is independent of the number of samples obtained.

ERROR LEVELS

In any sequential sampling plan, two statistical errors can be made. First, the population level may be determined to be below a certain critical threshold while in reality it is above; consequently one would fail to recommend treatment when it is necessary. This error is known as a Type I error and it has a probability of α. Second, the population may be overestimated, resulting in recommendations for unnecessary treatment. This constitutes a Type II error, where the probability is β.

It is more serious to fail to recommend a necessary treatment (Type I) than to recommend an unnecessary action (Type II), because the cost of the treatment is lower than the potential losses. Consequently, the probability of committing a Type I error (α) should be lower than the probability of committing a Type II error (β). The precision of the sampling plan increases as probabilities of errors I and II decrease, but the number of samplings required may become prohibitive. Most sequential sampling programs have error levels of about 0.05 to 0.1 (Sevacherian and Stern 1972; Pieters and Sterling 1974, 1975; Gruner 1975; Strayer *et al.*1977), and sometimes of 0.4 (Danielson and Berry 1978, Burts and Brunner 1981). When error level α is 0.05, there will be, on the average, one Type I error in every 20 decisions.

PRINCIPLES OF SEQUENTIAL SAMPLING

WALD'S PROCEDURE

Wald's sampling method (1947) is based on a theoretical mathematical distribution that can describe the observed spatial distribution of the insect population under consideration.

Probability curve

For each level of infestation, the probability curve, also named operating characteristic curve (Onsager 1976), indicates the probability of accepting hypothesis H_1, which assumes that the mean of the population sampled is equal to or below the value of λ_1 (Oakland 1950) (Fig. 2). The probability

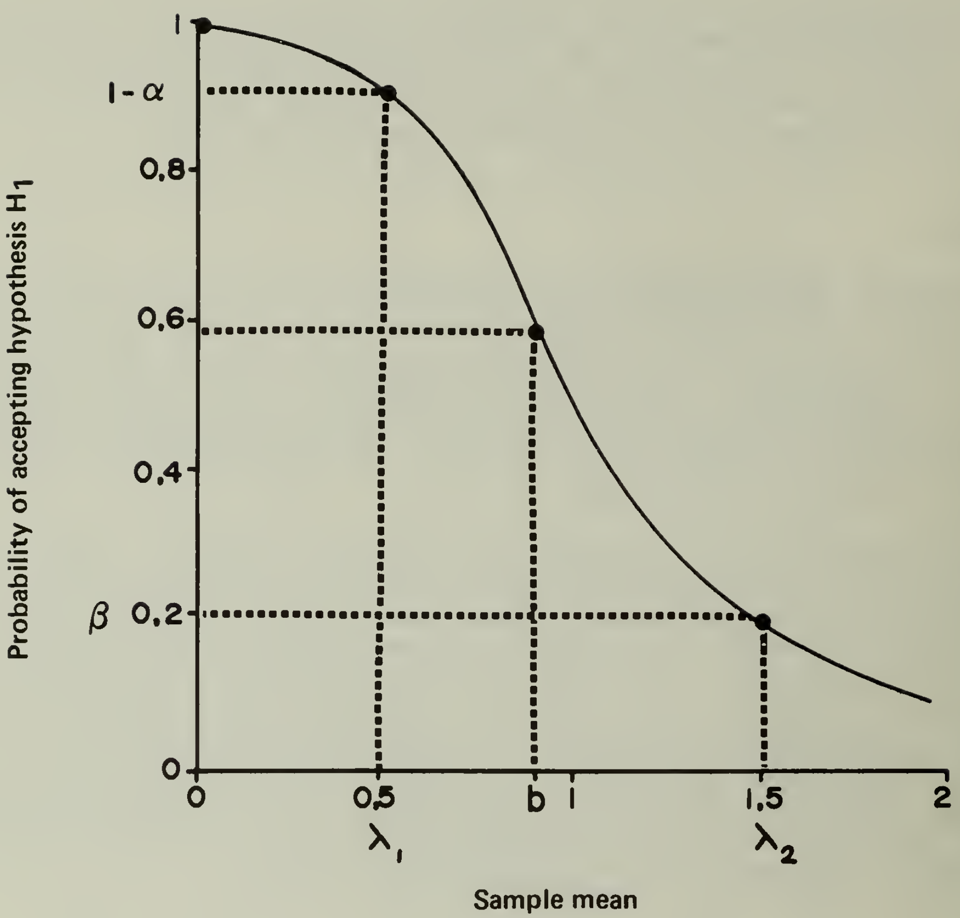

Fig. 2. Probability curve of a sequential sampling plan, using Wald's method.

of accepting hypothesis H_2, that is, that the population mean is higher than λ_2, follows an inverse curve. The slope of this curve depends on the values chosen for α and β.

Regardless of what the spatial distribution of the pest is, four points are calculated for interpolating the curve. These points are obtained as follows:

(1) for $\lambda' = 0$ $\quad LP = 1$

$\lambda' = \lambda_1$ $\quad LP = 1 - \alpha$

$\lambda' = b$ $\quad LP = a_2 / a_2 - a_1$

$\lambda' = \lambda_2$ $\quad LP = \beta$

where LP = level of probability
a_1 = Y intercept of D_1
a_2 = Y intercept of D_2
b = slope

Average sample number curve

This curve makes it possible to predict the mean number of samples that must be obtained before making a decision (Fig. 3). The number of samples varies with the level of infestation and is at a maximum near the economic threshold. If the prediction regarding the number of samples required exceeds available resources in terms of time and labor, the only remaining alternative is to sacrifice precision by increasing either the probability of errors I and II or the difference between λ_1 and λ_2.

The equations used to calculate four of the points in this curve are described below. The ordinate at the origin of this curve indicates the minimum number of samples that must be obtained before making a decision (Fig. 3).

Calculation of acceptance boundaries

Sequential sampling equations are given for two types of spatial distributions frequently found in pest control situations: Poisson and negative binomial distributions. The equations are from Wald (1947), Waters (1955), and Onsager (1976), who also give other equations that can be used with other types of distribution.

Poisson Distribution - This model is a probability distribution whose mean and variance have a common constant value. It is used to describe a population that is randomly distributed in space (Fig. 1B) (Southwood 1978). The only measurable parameter required to describe it is the mean ($\overline{X}$).

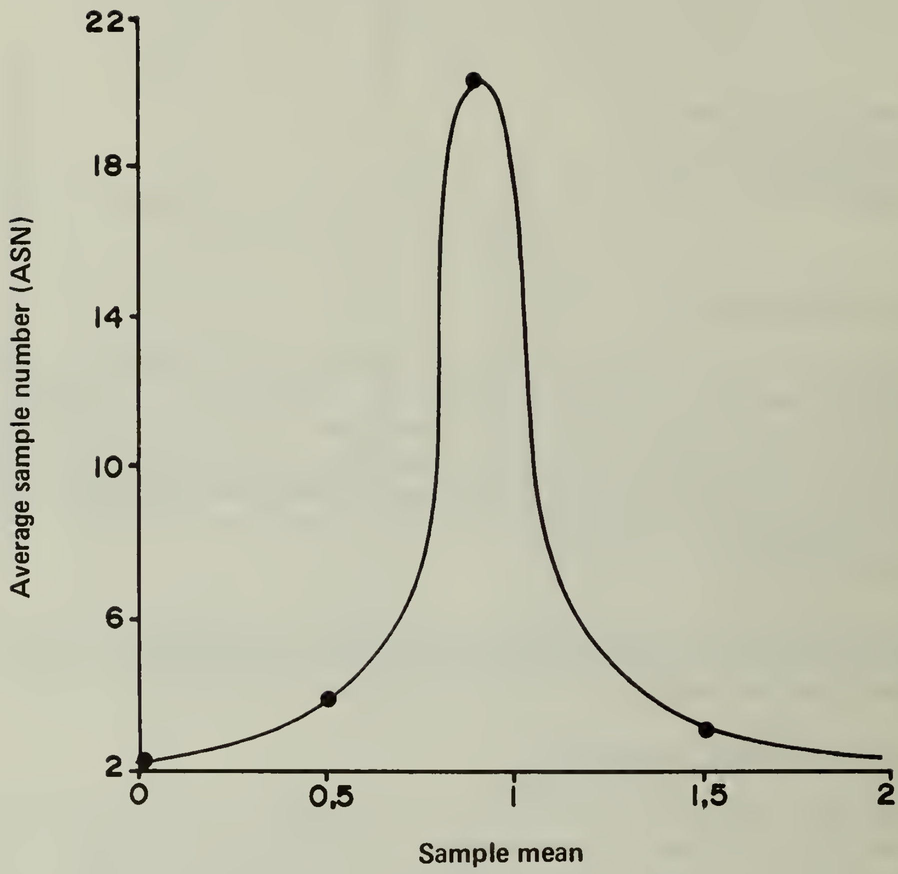

Fig. 3. Average sample number curve of a sequential sampling plan obtained by Wald's method.

Y intercept of D_1 (Fig. 4):

$$(5)\quad a_1 = -\frac{\log\left(\frac{1-\alpha}{\beta}\right)}{\log\left(\frac{\lambda_2}{\lambda_1}\right)}$$

Y intercept of D_2:

$$(6)\quad a_2 = \frac{\log\left(\frac{1-\beta}{\alpha}\right)}{\log\left(\frac{\lambda_2}{\lambda_1}\right)}$$

Slope of the two parallel lines:

$$(7)\quad b = \frac{0.4343\ (\lambda_2 - \lambda_1)}{\log\left(\frac{\lambda_2}{\lambda_1}\right)}$$

where α = probability of making a Type I error
β = probability of making a Type II error
λ_1 = population mean used as lower limit
λ_2 = population mean used as upper limit.

Average sample number curve (ASN):

$$(8)\quad ASN = \frac{LP\ (a_1 - a_2) + a_2}{\lambda' - b}$$

where LP = chosen level of probability at λ_1
λ' = population mean

There are two particular cases where the calculations are made in a different way:

where $\lambda' = 0$, LP = 1, and ASN = $a_1/-b$

$\lambda' = b$, ASN = $a_1 a_2/-b$

The peak of this curve indicates the maximum number of samples to be obtained, on the average, when the population density is near the economic threshold. This point is useful in deciding when to stop sampling in cases where no decision has been made (see "End of Sampling"). This peak is near the three values of ASN calculated for $\lambda' = 0$, $\lambda' = \lambda_1$, and $\lambda' = b$.

Negative Binomial Distribution - This model is used to describe a contagious distribution (Fig. 1C) (Southwood 1978). This distribution frequently observed in pest populations can be described by two parameters: the arithmetic mean and K, a constant used to measure the degree of aggregation of the population.

Acceptance boundaries based on a negative binomial distribution are calculated on the basis of four new parameters, as follows:

(9) $P_1 = \lambda_1/K$

(10) $P_2 = \lambda_2/K$

(11) $Q_1 = 1 + P_1$

(12) $Q_2 = 1 + P_2$

That K is constant, regardless of the level of infestation, is one of the underlying hypotheses in the use of sequential statistics. If the value of K increases with the sample mean, a common K, denoted K_c, can be calculated for all the means (Bliss and Owen 1958). If K_c has not been determined for the pest population under consideration, it is necessary to ensure that K is almost constant for the range of means covered by the sequential sampling plan (Onsager 1976).

Y intercept of D_1 (Fig. 4):

(13) $$a_1 = -\frac{\log\left(\frac{1-\alpha}{\beta}\right)}{\log\left(\frac{P_2Q_1}{P_1Q_2}\right)}$$

Y intercept of D_2:

(14) $$a_2 = \frac{\log\left(\frac{1-\beta}{\alpha}\right)}{\log\left(\frac{P_2Q_1}{P_1Q_2}\right)}$$

Slope of the two parallel lines:

(15) $$b = K\,\frac{\log\left(\frac{Q_2}{Q_1}\right)}{\log\left(\frac{P_2Q_1}{P_1Q_2}\right)}$$

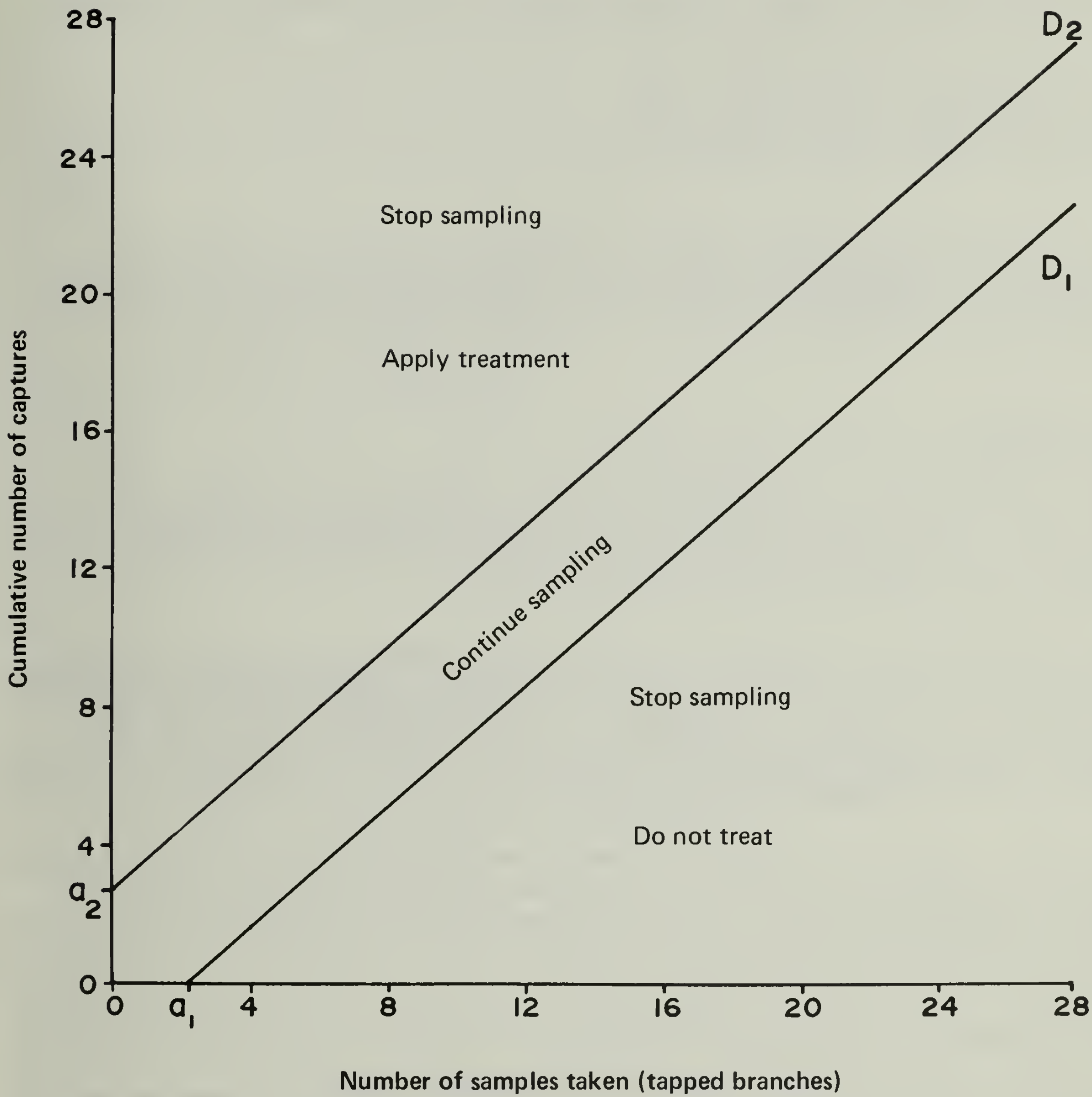

Fig. 4. Acceptance boundaries of a sequential sampling plan according to Wald's method.

Average sample number curve (ASN):

$$(16)\quad ASN = \frac{a_2 + (a_1 - a_2)\ LP}{\lambda' - b}$$

There are two special cases where the calculations are obtained in a different way:

where $\lambda' = 0$, $LP = 1$, and $ASN = a_1/-b$

$\lambda' = b$, $ASN = a_1 a_2/-(b^2/K + b)$

When α is equal to or smaller than β, the peak of the ASN curve approaches the value of ASN calculated for $\lambda' = b$. As the value of α increases over the value of β, the accuracy of the estimate decreases, and the exact value must be found by iteration by means of equation 16 (Onsager 1976).

End of sampling

When the actual mean of the population falls between the two chosen limit values (λ_1 and λ_2), it is possible to take a large number of samples without going outside these limits and remain incapable of reaching a decision. Therefore, a mechanism must be provided to make it possible to end the sampling process.

Wald (1947) proposed a mathematical solution that takes into account changes at the level of α and β errors, but this solution requires complex mathematical calculations. Waters (1974) suggested that sampling should stop when the maximum number of samples predicted by the average sample number curve has been reached. Nevertheless, he does not explain how we can choose between hypotheses H_1 and H_2 once the sampling has stopped.

Some authors suggested that sampling should be started again at a later point in time (Sevacherian and Stern 1972) or that the hypothesis represented by the acceptance boundary closest to the last sampled point should be accepted (Sterling and Pieters 1974, 1975).

IWAO'S PROCEDURE

Mean crowding (Lloyd 1967) is an aggregation index that can be obtained as follows:

$$(17)\quad \overset{*}{X} \simeq \bar{X} + (\frac{s^2}{\bar{X}} - 1)$$

The mathematical relationship between mean density ($\bar{X}$) and mean crowding ($\overset{*}{X}$)

describes certain characteristics of the spatial distribution that are inherent to each species in a given habitat. Iwao (1968) demonstrated that this relationship can be described by a simple linear regression.

There are two parameters that describe the type of spatial distribution of the organism: the Y intercept of the regression line (a_r), that is, the index of basic contagion; and the slope of the regression (b_r), that is, the density-contagiousness coefficient. The first of these parameters characterizes the basic unit of the population, whereas the second describes the distribution of these units in space. Regression validity must be checked in terms of the significance of the correlation coefficient (Steel and Torrie 1980).

Contrary to Wald's method, the economic threshold is used directly to calculate the limits of the acceptance curves. The following equations are from Iwao (1975) and Southwood (1978).

Curve of the upper acceptance limit

$$(18) \quad C_s = N \times ET + t \sqrt{N \left[(a_r + 1)\, ET + (b_r - 1)\, ET^2\right]}$$

Curve of the lower acceptance limit

$$(19) \quad C_i = N \times ET - t \sqrt{N \left[(a_r + 1)\, ET + (b_r - 1)\, ET^2\right]}$$

where C = total captures
N = number of samples taken
ET = economic threshold
t = value of Student's t at chosen level of significance for a two-sided test and an infinite number of degrees of freedom
a_r = index of basic contagion (Y intercept)
b_r = density-contagiousness coefficient (slope)

Two curves are obtained by calculating several C_s and C_i for different values of N (Fig. 5). The space between these two curves increases with the amplitude of the degree of precision. If the population mean of the target population is equal to the economic threshold, a large number of samples can be obtained in between the calculated limits. Iwao's procedure makes it possible to calculate the maximum number of samples that must be taken in order to determine if the population level is equal to the economic threshold, within a predetermined confidence band.

Maximum number of samples

$$(20) \quad N_{(max)} = \frac{t^2}{d^2} \left[(a_r + 1)\, ET + (b_r - 1)\, ET^2\right]$$

where d = confidence interval of the estimated mean density (see example)

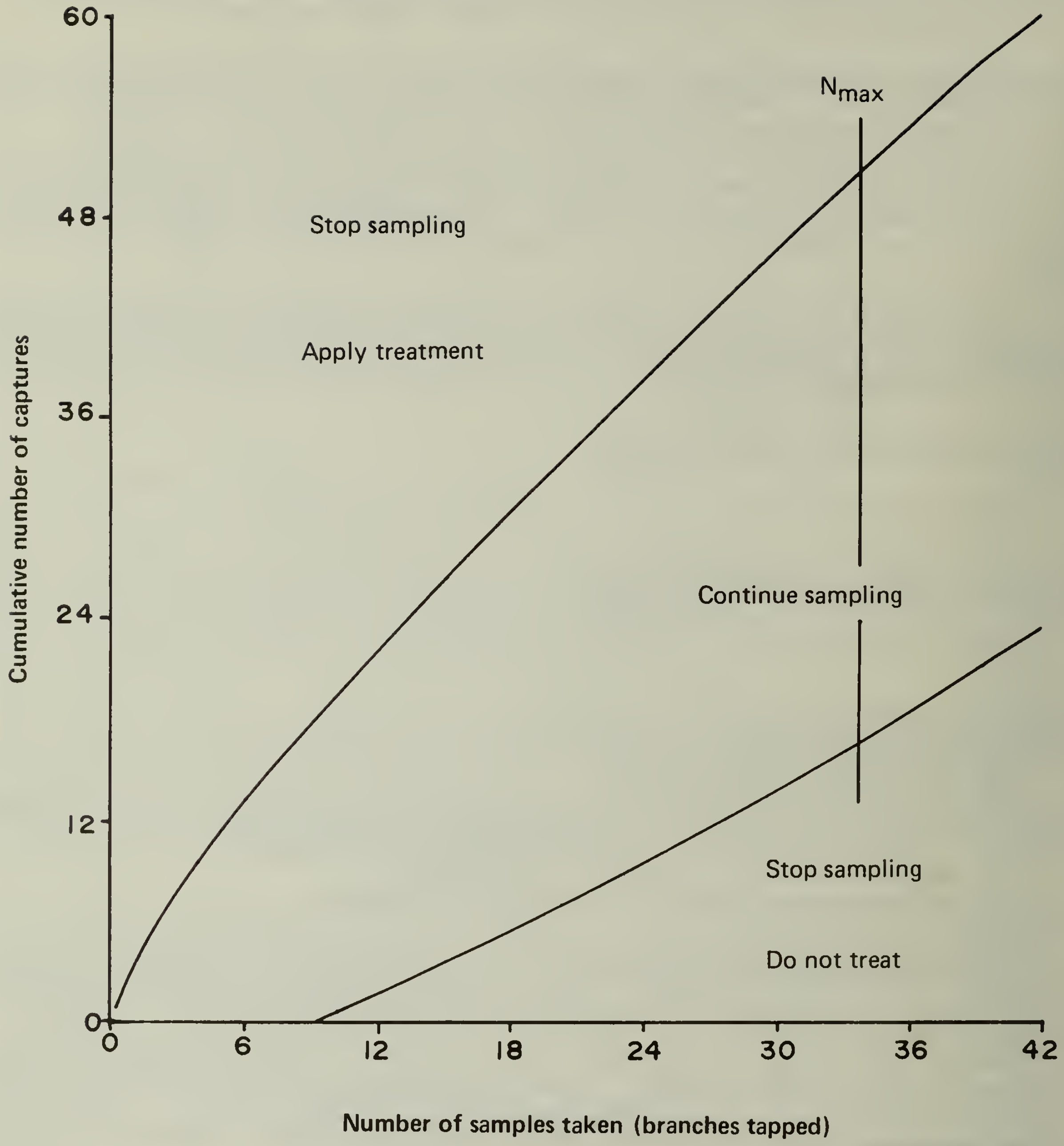

Fig. 5. Acceptance curves of a sequential sampling plan, according to Iwao's method.

This procedure takes into account the possibility that the mean and economic threshold might be the same. When sample N_{max} is reached, one decides that the population mean is at the economic threshold and a decision can then be made.

USING THE SAMPLING PLAN - EXAMPLE

We have so far described the sampling plan in graphic terms. Some authors (Onsager 1976, Mason 1978) have examined the difficulties involved in using graphic methods in the field and have proposed the use of tables (Tables 1 and 2). For each sampling intensity, the table gives the values of cumulated captures for each limit. The cumulative captures are compared to the lower and upper limits at the appropriate number of samples.

An example is presented here wherein the methods of Wald and Iwao can be practically compared. This example uses the sampling technique and spatial distribution used with early nymphs of *Lygocoris communis* (Knight) (Hemiptera: Miridae) (Boivin 1981). This sampling technique, whose effectiveness and reliability have already been evaluated, consists of tapping apple branches over a white cloth measuring 1 m^2. A provisional economic threshold of one first- or second-instar nymph per branch tapped is used. When the population density is above this threshold, treatment is required, while populations below this level are tolerated.

WALD'S PROCEDURE

The spatial distribution of early *Lygocoris communis* nymphs is described by a negative binomial distribution with K = 2.13. Population means specified as the lower and upper limits are $\lambda_1 = 0.5$ and $\lambda_2 = 1.5$ nymphs per branch; error limits are $\alpha = 0.1$ and $\beta = 0.2$.

$$P_1 = 0.5/2.13 = 0.2347$$
$$P_2 = 1.5/2.13 = 0.7042$$
$$Q_1 = 1 + 0.2347 = 1.2347$$
$$Q_2 = 1 + 0.7042 = 1.7042$$

<u>Y intercept of D_1</u>

$$a_1 = -\frac{\log\left(\frac{0.9}{0.2}\right)}{\log\left(\frac{0.7042 \times 1.2347}{0.2347 \times 1.7042}\right)} = -\frac{\log 4.5}{\log 2.1738} = -\frac{0.6532}{0.3372} = -1.9370$$

<u>Y intercept of D_2</u>

$$a_2 = \frac{\log\left(\frac{0.8}{0.1}\right)}{\log\left(\frac{0.7042 \times 1.2347}{0.2347 \times 1.7042}\right)} = \frac{\log 8}{\log 2.1738} = \frac{0.9031}{0.3372} = 2.6782$$

Table 1. Acceptance limits of hypotheses H_1 and H_2 for a sequential sampling plan according to Wald's procedure

Number of samples (branches tapped)		Lower limit		Upper limit	
1		-		4	
2		-		4	
3		1		5	
4		2		6	
5	STOP SAMPLING AND TOLERATE THIS POPULATION LEVEL	2	CONTINUE SAMPLING	7	STOP SAMPLING AND APPLY TREATMENT
6		3		8	
7		4		9	
8		5		10	
9		6		11	
10		7		12	
11		8		12	
12		9		13	
13		10		14	
14		10		15	
15		11		16	
16		12		17	
17		13		18	
18		14		19	
19		15		19	
20		16		20	
25		20		25	
30		25		29	
35		29		34	

Table 2. Acceptance limits of hypotheses H_1 and H_2 for a sequential sampling plan according to Iwao's procedure

Number of samples (branches tapped)		Lower limit		Upper limit	
1		-		4	
2		-		6	
3		-		8	
4		-		10	
5	STOP SAMPLING	-	CONTINUE	11	STOP SAMPLING
6	AND TOLERATE	-	SAMPLING	13	AND APPLY
7	THIS POPULATION	-		15	TREATMENT
8	LEVEL	-		16	
9		0		18	
10		0		19	
11		1		21	
12		2		22	
13		2		23	
14		3		25	
15		4		26	
20		7		33	
25		10		40	
30		14		46	
35		18		52	
40		22		58	
45		25		64	
50		29		70	

Slope of the lines

$$b = 2.13 \times \frac{\log \dfrac{1.7042}{1.2347}}{\log \dfrac{(0.7042 \times 1.2347)}{(0.2347 \times 1.7042)}} = 2.13 \times \frac{0.14}{0.3372} = 0.8841$$

These acceptance limits are shown in Fig. 4 and Table 1.

Probability curve

Four points on this curve make it possible to interpolate the general curve.

For $\lambda' = 0$	$LP = 1$
$\lambda' = 0.5$	$LP = 0.9$
$\lambda' = 0.8841$	$LP = 0.5803$
$\lambda' = 1.5$	$LP = 0.2$

This curve is illustrated in Fig. 2.

Average sample number curve

Four points are calculated to interpolate a complete curve:

For $\lambda' = 0$	$ASN = 2.1909$
$\lambda' = 0.5$	$ASN = 3.8414$
$\lambda' = 0.8841$	$ASN = 20.0045$
$\lambda' = 1.5$	$ASN = 2.8485$

Since α is smaller than β $(0.1 < 0.2)$, the maximum value of the mean number of samples will be close to the value of ASN for $\lambda' = 0.8841$, that is, 20 samples. The minimum number of samples to be obtained before making a decision is two samples (Fig. 3).

This sequential sampling plan makes it possible to decide whether the pest population level is above or below the acceptance limits, after obtaining a maximum number of 20 samples, on the average.

IWAO'S PROCEDURE

The parameters of the spatial distribution of early *Lygocoris communis* nymphs have been calculated in terms of the regression of mean crowding over the mean. In this case, $a_r = 1.68$ and $b_r = 1.47$, with $r = 0.91$ (significant, $\alpha \doteq 0.05$). The economic threshold is one individual per branch tapped and the error level α is 0.1. The values of Student's t, for infinite degrees of freedom, are 1.64 for $\alpha = 0.1$ and 1.96 for $\alpha = 0.05$.

Upper acceptance limit

$$C_s = N \times 1 + 1.64 \sqrt{N\,[(1.68 + 1) \times 1 + (1.47 - 1) \times 1^2\,]}$$

$$= N + 1.64 \sqrt{N \times 3.15}$$

Lower acceptance limit

$$C_i = N \times 1 - 1.64 \sqrt{N\,[(1.68 + 1) \times 1 + (1.47 - 1) \times 1^2\,]}$$

$$= N - 1.64 \sqrt{N \times 3.15}$$

Acceptance limits of these two curves are shown in Fig. 5 and Table 2.

It is possible to calculate the maximum number of samples to be obtained before estimating whether the population mean is equal to the economic threshold. An $\alpha = 0.1$ and $d = 0.5$ were chosen, which means that at N_{max}, the population mean is 1 ± 0.5 nymph per branch, with an error α of 0.1. This idea can also be expressed as follows: after N_{max} samples are obtained, nine times out of ten the estimated mean falls within the 0.5 - 1.5 interval.

Maximum number of samples

$$N_{max} = \frac{(1.64)^2}{(0.5)^2}\,[(1.68 + 1) \times 1 + (1.47 - 1) \times 1^2]$$

$$= \frac{2.6896}{0.25} \times 3.15$$

$$= 10.7584 \times 3.15$$

$$= 33.8890$$

Sampling stops after 34 samples have been obtained. We know that the population level is within the chosen interval and a decision as to whether to intervene or not can now be made.

CONCLUSIONS

The sequential sampling method makes it possible to determine a pest population level with a significant reduction in the number of samples required. Available information on the bioecology of the pest determines in part the choice of the most appropriate procedure. In our opinion, Iwao's procedure has three advantages.

- It does not require a theoretical mathematical model approaching the spatial distribution of the insect.

- The population mean is evaluated in relation to an economic threshold and not an arbitrary interval.

- Sampling stops when the mean of the population sampled and the error levels are known.

Whatever the procedure chosen, available resources can be used more efficiently. Given that the time spent in sampling is one of the main problems associated with a detection program, the use of a sequential sampling method represents a more attractive systematic detection alternative. Significant reduction in costs is another important argument that can be used to persuade farmers to follow integrated pest control programs. We are thus convinced that sequential sampling is a step forward in the implementation of integrated pest management programs.

GLOSSARY OF SYMBOLS

a_1 = Y intercept of D_1 (Wald)

a_2 = Y intercept of D_2 (Wald)

ASN = average sample number (Wald)

a_r = index of basic contagion, Y intercept of the regression line (Iwao)

b = slope

b_r = density-contagiousness coefficient, slope of regression line (Iwao)

C_i = curve of lower acceptance limit (Iwao)

C_s = curve of upper acceptance limit (Iwao)

d = confidence interval of the estimated mean density (Iwao)

D_1 = upper acceptance limit of H_1 (Wald)

D_2 = lower acceptance limit of H_2 (Wald)

ET = economic threshold

H_1 = hypothesis according to which one sample is equal to or below a preestablished level

H_2 = hypothesis according to which one sample is equal to or above a preestablished level

K = constant, measure of aggregation

K_c = common K

LP = level of probability (Wald)

N = number of samples taken

N_{max} = maximum number of samples to be obtained before being able to decide whether the mean is equal to the economic level (Iwao)

P = calculated parameter (Wald)

Q = calculated parameter (Wald)

s^2 = sample variance

t = value of Student's t at chosen level of significance

$\bar{X}$ = sample mean

$\overset{*}{X}$ = mean crowding (Iwao)

α = probability of a Type I error

β = probability of a Type II error

λ_1 = mean of sample chosen as lower limit (Wald)

λ_2 = mean of sample chosen as upper limit (Wald)

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